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THE CHALLENGES OF USING AN UNCOOLED MICROBOLOMETER ARRAY IN A THERMOGRAPHIC APPLICATION

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1.0 Abstract & Introduction

Microbolometer based camera systems have made their way into the mainstream of readily available IR imagers. With the realized advantages over cooled systems of lower power consumption, short turn-on time, and higher reliability, these cameras are the clear choice for any application requiring true hand held operation. Until recently, these uncooled systems were limited to output of a video image that displayed scene temperature differences.

Now the first generation of uncooled thermography cameras are beginning to become available. The ExplorIR thermography camera makes use of some of the proven components from Raytheon Amber's microbolometer imaging camera, the Sentinel [1]. For this new camera, a temperature measurement accuracy specification of 4° C or 4% of the measured value (from -20° to 300° C or -20 to 900° C) has been demonstrated at camera environmental temperatures from -10° C to 40° C. Striving to maintain common components between the two systems has resulted in reduced non-recurring engineering and lower manufacturing costs.

However, new challenges arise when the radiometric accuracy that is required for direct temperature measurements of the scene becomes as important as the production of a high quality video image. Specifically, the lack of a field of view shield to limit environmental radiation results in large changes in DC output and degradation to the non-uniformity correction as the camera's environmental temperature changes. To compensate for output drift and added non-uniformity from environmental temperature changes, the ExplorIR camera incorporates a level adjustment circuit, and a temperature monitored shutter situated in the lens. Long term gain stability, becomes even more critical as factory preset gain values for each pixel, that are expected to be valid for the life of the camera, must permit the camera to maintain the specified temperature measurement accuracy. Optical properties of the lens material vs. environmental temperature must also be taken into account. Depending on the doping characteristics of the Ge used in the lens, the change in overall transmission over the -10° to 40° C operating temperature range can be as high as 8%.

This paper will give an overview of the camera and the general methods used for radiometric calibration. The specific obstacles to obtaining radiometric accuracy and preserving dynamic range will be discussed along with the approaches used to overcome those problems. Most importantly, the end result of these efforts, measured radiometric accuracy will be presented.

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14. ABSTRACT
Microbolometer based camera systems have made their way into the mainstream of readily available IR imagers. With the realized advantages over cooled systems of lower power consumption, short turn-on time, and higher reliability, these cameras are the clear choice for any application true hand held operation. Until recently, these uncooled systems were limited to output of a video image that displayed scene temperature differences.

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2.0 Camera Overview

The ExplorIR Camera can be divided into two functional groups, a sensor engine produced by Raytheon Amber and a camera package produced by Nippon Avionics Company. The sensor engine has three main components, a dewar/thermoelectric (TE) cooler package, an array interface board and a digital processing board. The dewar package consists of a 320 x 236 element, 50 μm pitch FPA with sensitivity in the long wavelength infrared, a TE cooler package for temperature stabilization and the metal enclosure with a 1 inch diameter germanium window. The array interface board, handles the generation of FPA bias voltages, the TE cooler temperature control and 12 bit A/D conversion of the output signal. The digital board produces the FPA timing signals, handles non-uniformity correction, "bad" pixel substitution and communication between the sensor engine and the camera's processor. The camera package consists of a processor, video display, onboard temperature sensors, digital image storage, optics and a physical package. The processor handles camera control functions and radiometric conversion of digital counts from the sensor engine to temperature. The video display is a 5 inch flip out, color, LCD panel, viewable in full sunlight. The onboard temperature sensors monitor camera internal temperature, camera ambient temperature for use in emissivity correction of target temperature, and camera lens temperature to correct for changes in sensor output from changes in environmental temperature. Digital image storage is achieved through Compact Flash memory cards that can store up to 50 images on a 10 MB card. These cards (with a supplied adapter) can then be inserted directly into type II PCMCIA card reader for easy PC access to the digital images.. The camera's standard lens is a three element f/1.0, 35 mm focal length lens with transmission optimized for 8-14 μm.

Figure 1 shows the ExplorIR camera with the 5 inch LCD screen open. The battery, video output jack, headset jack (for audio annotation of captured images) and power switch are visible on the back of the camera.

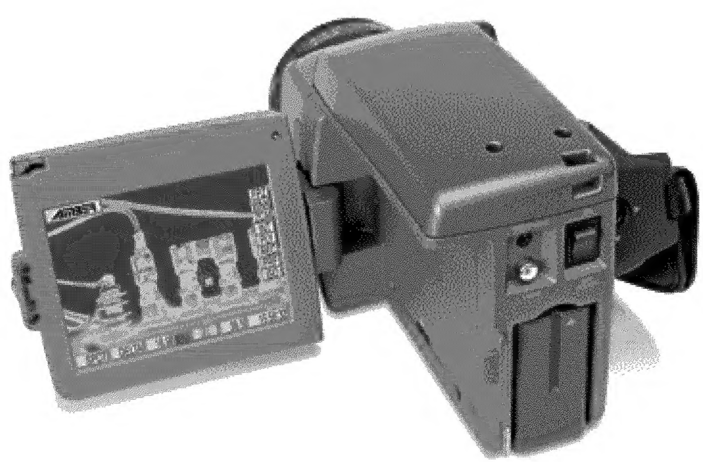

Figure 1. ExplorIR camera with display open

2.1 Temperature Measurement and Radiometric Calibration

The ExplorIR camera allows the user to display real time temperature measurements of objects anywhere in the displayed scene. Up to two measurements can be displayed simultaneously by placing measurement cross hair overlays on the displayed image. The camera's temperature readout then displays the average temperature for the 3 x 3 group of pixels in the center of the cross hair. If the displayed image is either captured to storage and redisplayed or frozen on the screen, the user can manipulate the cross hairs to generate temperature information on any area of the image. The specification on temperature measurement accuracy of +/- 4° C or 4% of the measurement (whichever is greater) is valid across the whole display area. The standard range camera measures temperature between -20° C and 300° C. The extended range camera measures temperatures from -20° C to 900° C. The higher temperature range for the extended range camera is achieved by manually sliding a built-in neutral density filter into the optical path between the dewar and lens. The camera senses the location of the filter and automatically applies the correct radiometric calibration.

3.0 Non-uniformity Correction and Temperature Conversion

Under the ideal circumstances of zero signal contribution from a changing environment, radiometric calibration and accuracy across the whole image depends on two things, a good non-uniformity correction and an accurate conversion from digital counts to temperature. Non-uniformity correction (NUC) is performed as a three step process. First, a gross non-uniformity correction (4 bits) is applied to the signal "on-chip" [2]. By placing some of the non-uniformity correction ahead of the A/D converter, more of the A/D converter's dynamic range is available to handle changes in IR input. Without on-chip correction a more expensive 16 bit A/D converter would be needed to handle the requirements for dynamic range while maintaining the same size least significant bit. This on-chip correction is determined during FPA level screen testing. The second step in the NUC process is a determination of individual pixel gains by normalization of the FPA responsivity. This step takes place either at the sensor engine level or after final camera assembly is completed. The pixels gains are applied to the digital video stream right after A/D conversion. Pixel responsivities and thus the gain terms in the NUC are assumed to be valid for the life of the camera and as such are stored in camera permanent memory and applied at power up. The third step in the NUC process is the generation of offset coefficients. New offset coefficients are calculated and applied at start-up and following the closing of the camera's shutter.

3.1 Temperature Conversion

An algorithmic approach was chosen for the conversion from corrected digital units to temperature output. A fourth order polynomial was picked as the function which would relate counts to temperature, where counts are linearly proportional to the total power incident on a detector. A selected number of blackbody temperatures are used to gather the data points from which the polynomial is generated.

$$C = A_0 + A_1T + A_2T^2 + A_3T^3 + A_4T^4$$

where: C = Digital Counts, T = Object Temperature
The coefficients A_0 ...A_4 are determined by selecting a least squares fit for camera digital output when viewing various blackbody reference sources.

The coefficients B_0...B_4 for the inverse function, that relates temperature to digital counts are computed at the same time and used by the camera for object temperature measurement.

$$T = B_0 + B_1C + B_2C^2 + B_3C^3 + B_4C^4$$

Figures 2 and 3 show fourth order polynomial curve fits and the polynomial coefficients for blackbody temperature versus simulated camera A/D counts and the inverse function, counts versus temperature. The data points for these curve fits are calculated, based on camera parameters and are representative of the data points that are used for an actual camera calibration.

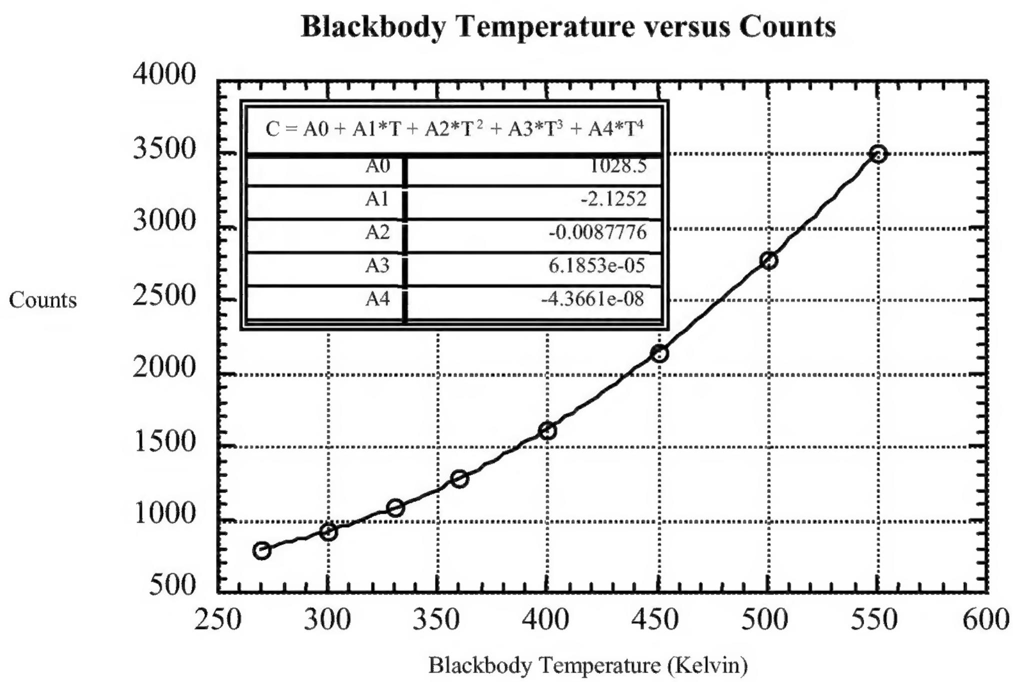

Figure 2. A fourth order polynomial is used to relate A/D signal, "counts" to blackbody temperature.

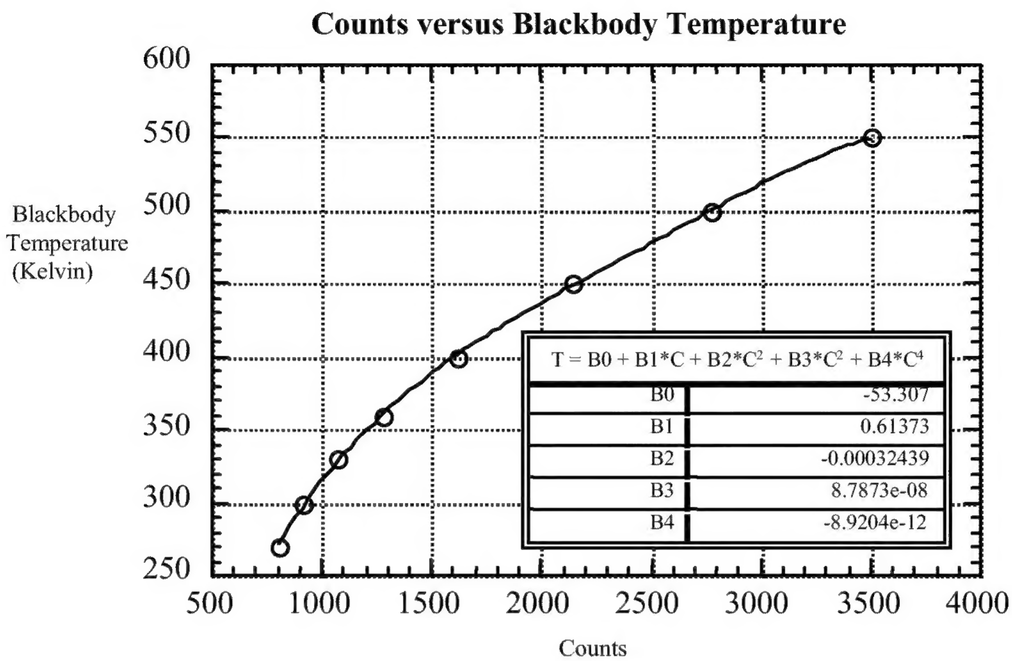

Figure 3. An inverse fourth order polynomial relationship is used to relate blackbody temperature to counts.

3.2 Correction for Emissivity

In order to get more accurate temperature measurements from "greybodies," (objects with emissivities less than 1), both the emissivity and the apparent background temperature must be known or at least estimated. The emissivity and apparent background temperature get folded into the above equations in the following way.

$$C = \alpha + e(A_1T + A_2T^2 + A_3T^3 + A_4T^4)$$

and $\alpha = A_0 + (1 - e)(A_1T_a + A_2T_a^2 + A_3T_a^3 + A_4T_a^4)$

where Ta is the apparent background temperature that is partially reflected off the measured object.

$$T = \beta + (1/e)(B_1C + B_2C^2 + B_3C^3 + B_4C^4)$$

and $\beta = B_0 + (1 - 1/e)(B_1C + B_2C^2 + B_3C^3 + B_4C^4)$

3.3 Pixel Gain Stability

Pixel responsivity stability is a critical aspect of this camera design since the gain coefficients of the NUC for each pixel are programmed during camera assembly. If pixel responsivities change over time the result will be added non-uniformity in the image and degraded measurement accuracy; less accurate measurements for each pixel and more variation between pixels. To answer the question of how pixel responsivities vary over time, gain stability data was gathered on a Sentinel camera, by comparing responsivity measurements taken more than 14 months apart. To see the variation in responsivity, one responsivity array was divided by the other so that the result was an array of pixel responsivity ratios. This array was normalized to have mean of 1.00. Figure 4 is a histogram plot of this normalized array. The maximum and minimum pixels in the array have responsivities that have varied by 3%, while the one sigma value for responsivity variation is less than 1%, at 0.0095. At first glance it might appear that a maximum responsivity variation of 3% is cause for concern. However, typical responsivity measurements made directly after non-uniformity correction still show peak to peak variations that are roughly 2% across the FPA, so this type of variation is not excessive and likely more a measure of output drift during data acquisition. Additionally, the spatial distribution for the pixels with the largest variation is random, thus the effect on any 3 x 3 block of pixels used by the spot meter for temperature measurement is likely to be much smaller.

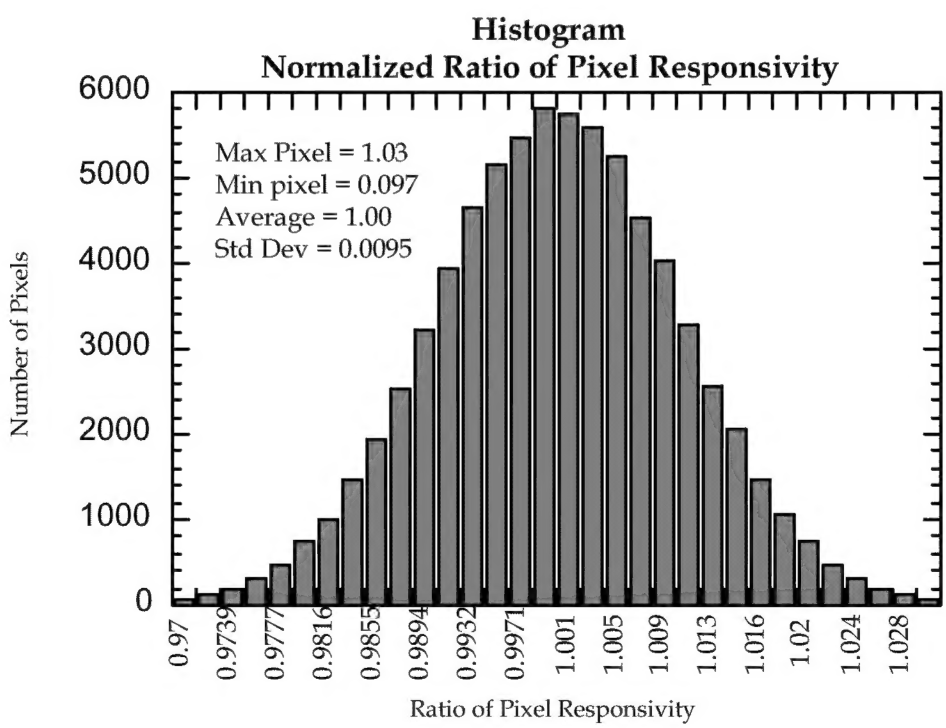

Figure 4. Array responsivity drift has been measured over a fourteen month period. The one sigma drift is less than 1%.

4.0 Operating Difficulties and Solutions

Unfortunately the preceding general description of the camera and radiometric calibration process don't tell the full story. Several challenges arise when environmental operating conditions are also considered. First of all, the camera's output includes a component that is dependent on the operating temperature; specifically the temperature of the lens and the dewar. In addition to this DC offset that must be handled, the transmission of the lens changes slightly with environmental temperature, creating the need for slight adjustment to the gain terms for each pixel.

4.1 Environmental Drift

Changes in the camera's operating temperature can occur for several reasons. The camera may be brought from room temperature into a hotter or colder environment outdoors. Even in a stable indoor environment the camera's temperature may change over the course of operation due to power dissipation from internal components. Whatever the cause of the change in operating temperature, there is a corresponding change in the FPA's output level. This is understandable and expected for the dewar design used in this camera. Unlike a conventional cooled dewar, there is no field of view shield to limit the radiation from sources outside the field of view of the lens. Thus, the FPA "sees" a full hemisphere of signal. For an f/1 optical system, the ratio of desired signal (signal from the imaged scene) to background is 1 to 5. At any instant in time, this does not create a problem since the background level contributes a DC level that may be corrected. However, over time as the camera's temperature changes, the DC level should change at a rate five times faster than the camera responds to scene temperature changes. This output drift with environmental temperature creates two problems. The first problem is that the usable dynamic range for actual changes in scene temperature is severely reduced. The second problem is that the temperature calibration coefficients need to be accurately updated.

4.1.1 Dynamic Range and Level Adjustment

Figure 5 shows average FPA output in counts versus camera environmental temperature from 10° C to 52° C. This data was acquired by placing the sensor engine (SE) portion of the camera in an environmental chamber and varying the chamber's temperature while the SE viewed a 25° C blackbody that filled the field of view of the lens. With the input from the scene constant, all changes in the output are due to the described environmental drift. As can be seen from the data, a change in the operating temperature of 42 ° C creates a roughly 2000 count change in the digital output. This is almost 1/2 of the full 12 bit (4096 count) dynamic range. With about 1000 counts taken up by FPA non-uniformity, there would be barely 1000 counts of usable dynamic

range. In addition to the change in DC level, there is also a significant amount of non-uniformity that is added to the image, if not corrected.

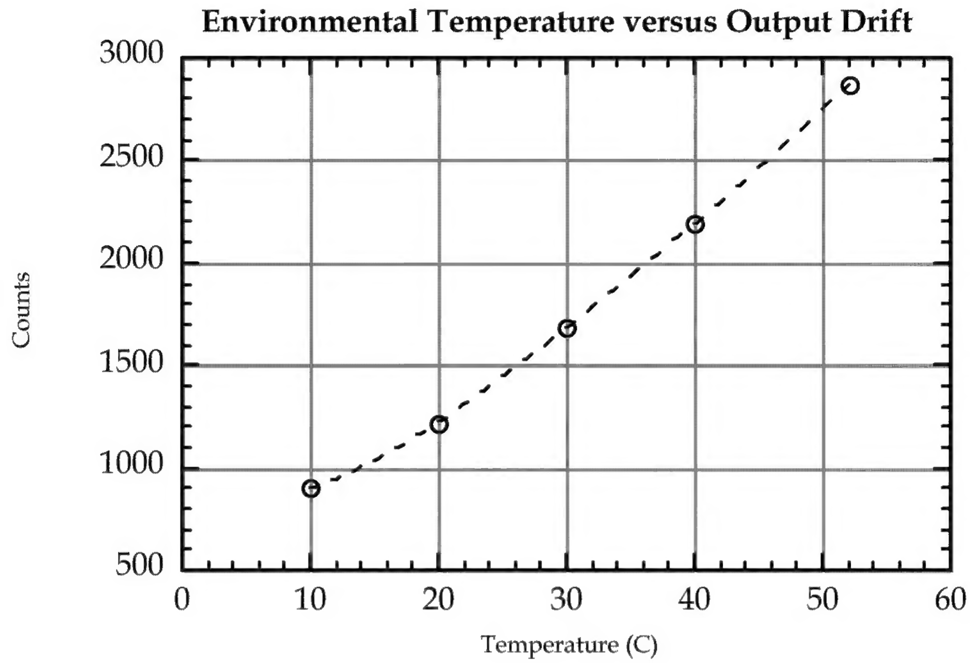

Figure 5. As the camera ambient temperature changes, a significant portion of the dynamic range is used up.

To recover the dynamic range that is lost by environmental drift, the camera has a built in level adjustment routine that changes the analog output signal offset prior to A/D conversion. The following sequence of steps are performed in this routine:

1. Determine an adjustment is required.
2. Close the shutter located in the lens. Freeze video output.
3. Acquire a frame of output and compare the level to the target value.
4. Calculate the required offset and command the offset DAC to the new setting.
5. Acquire new frames to update digital NUC offset coefficients.
6. Open shutter. Unfreeze video output.
7. Apply new offset coefficients.

This adjustment sequence is initiated either by an internal temperature sensor or by an interval timer that is adjustable by the user. This entire process takes about 0.5 seconds.

4.1.2 Radiometric Calibration

Each time the level into the A/D converter is adjusted for environmental temperature drift, the constant terms in the temperature calibration equations need to be adjusted. Proper adjustment is possible because the shutter in the lens is temperature monitored. As the frames for offset NUC are gathered, the temperature of the shutter is read. The mean output level (in digital counts), computed for the offset NUC is then compared to the predicted output level, based on the temperature of the shutter. The constant terms A_0 and B_0 are then updated so that the equations for temperature and counts agree with the new measurements.

4.2 Lens Transmission Changes

It is a well known fact that Germanium is a poor transmitter at high temperatures; especially in the LWIR. Since most of the curves available in handbooks emphasize this effect for temperatures above 100° C, at first glance it might not seem that an instrument operating at temperatures ranging from -10° C to 40° C would need to take transmission loss into consideration. However, measurements of responsivity at various environmental temperatures indicate that the difference in transmission between 0° C and 40° C is about 8%, twice the total temperature measurement error allowed for the system. Figure 6 shows normalized lens transmission as a function of environmental temperature. Each data point is the average of three different lens/camera transmission measurements. Clearly, lens transmission changes must be accounted for if radiometric accuracy is to be maintained.

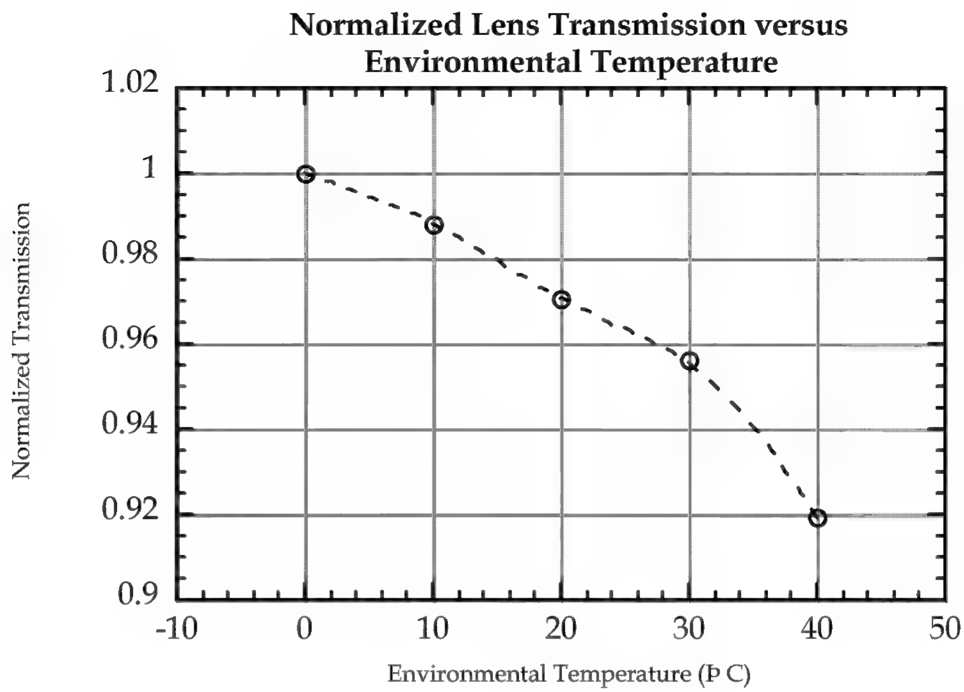

Figure 6. The transmission behavior of the Germanium optic causes sufficient change in transmission to warrant a correction.

4.2.1 Compensation for Transmission Changes

To compensate for these transmission changes, the effect is first characterized for each lens and camera combination. (This process is presently time consuming and will likely be replaced by a universal characterization when sufficient data has been gathered). Once the lens has been characterized, a table that relates lens temperature to transmission is constructed and loaded into the camera. This table is used by the camera to globally modify the gain coefficients for each pixel. The new pixel gain term used by the camera is then:

$$New\_gain_{pixel(x,y)} = Old\_gain_{pixel(x,y)} * (1 / Transmission)$$

Automatic compensation is made possible by programming the camera to monitor the temperature sensor located in the lens and adjust the gain terms based on that lens temperature measurement.

5.0 Temperature Measurement Accuracy

The approach for radiometric calibration and the solutions to some of the problems encountered along the way are only of interest if they result in the desired camera performance. The quantified temperature measurement accuracy of the camera makes the rest of this paper worthwhile. The camera's accuracy is well within the original design specification, and for the higher blackbody temperatures is significantly better than was generally expected.

5.1 Data Collection Information

Temperature measurement accuracy data was collected for both the standard range (-20 to 300° C) and extended range (-20 to 900° C) cameras. Object temperatures below 100° C were generated by a Santa Barbara Infrared extended area blackbody source. Temperatures above 100° C were generated by a Graseby cavity type blackbody. Environmental temperature was controlled by placing the camera inside an environmental chamber capable of maintaining temperature to +/- 0.1 ° C . The blackbody sources were placed outside the environmental chamber, and imaged by the cameras through a small opening in the chamber.

Measurements of the blackbodies were made by manually reading and recording spot meter values as displayed by the camera. The readings varied by a few tenths of a degree in real time at the lower target temperatures. This is to be expected based on the specified NEDT of 0.15 ° C at a blackbody temperature of 30 ° C.

5.2 Temperature Measurement Results

Both the standard range and extended range cameras gave temperature readings that were within their specified temperature measurement accuracy (4° C or 4% of the measured value) over the full environmental temperature range. For higher target temperatures, the extended range camera was very accurate, typically within 1% of the actual blackbody temperature. Figure 7 shows temperature measurement error as a function of blackbody target temperature at environmental temperatures of -10° C, 20° C and 40° C for the standard range camera. Figure 8 shows temperature measurement error versus blackbody temperature for the extended range camera. The extended range data was all taken at room temperature.

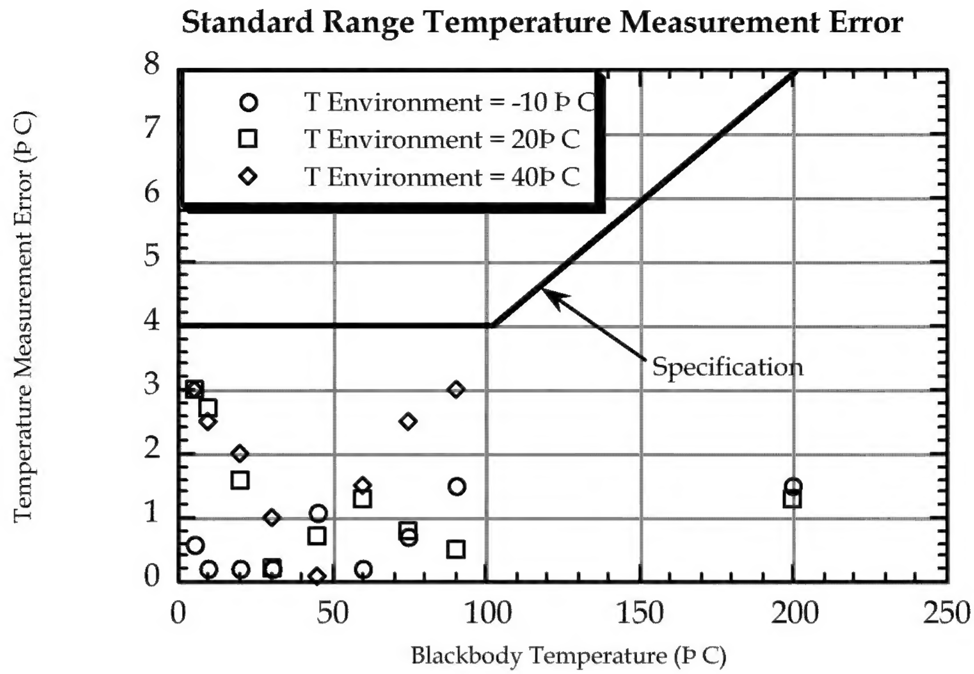

Figure 7. Temperature measurement error versus blackbody temperature for three different environmental temperatures.

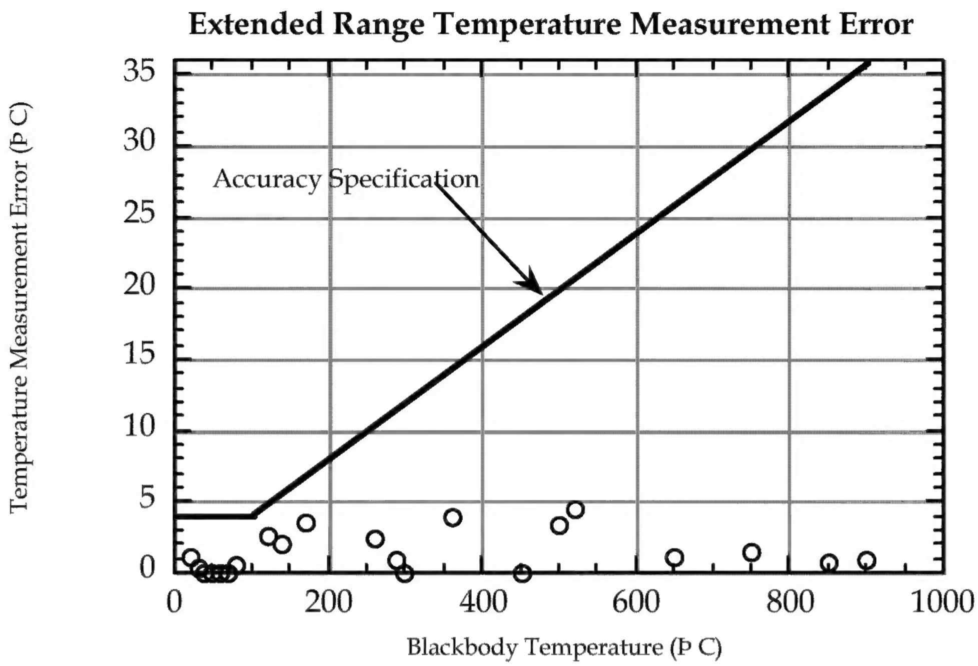

Figure 8. Temperature measurement error for the extended range camera was significantly below
the design specification at high blackbody temperatures.

6.0 Conclusion

Some of the challenges encountered in development of this camera are to be expected for any radiometrically calibrated camera; others like the large drift from environmental temperature change are a direct result of the direction that microbolometer development is headed. Smaller, lower cost vacuum packages are desired in an effort to reduce the overall production costs of IR systems. These small packages have no room (either physically or economically) for placement of a temperature stabilized field of view shield. Location of such a radiation shield outside the vacuum package would drive up system power dissipation in a way that would preclude portable operation. The methods used on this camera to combat environmental drift and its associated problems are not the only ones possible, just as there are other methods possible for radiometric calibration and lens transmission changes. However, in the end, the design goals of NEDT and temperature measurement accuracy for a handheld camera were met and in some instances significantly exceeded.

7.0 Future Work

There are several areas of potential future development for this camera. The possibility of adding a real time 12 bit digital output is presently being considered. The format for this output will likely conform to the Firewire (IEEE 1394) standard and will give users the ability to capture real time sequences with a PC. A redesign of the analog circuitry to make better use of today's higher responsivity microbolometers, would make possible a camera with more dynamic range and an NEDT of less than 0.075 ° C; one half the specified NEDT of today's cameras. As with any handheld device, reduced weight is always desirable. The camera's lens and housing are being examined to see how weight reduction can be achieved. Increasing microbolometer sensitivity will also allow a larger trade space for examining weight, price and performance tradeoffs. For example, a factor of 4 improvement in sensitivity for microbolometers over the baseline assumed during camera development would allow a f/2 lens to be used; dramatically reducing the cost of the optic and the lens contribution to the overall camera weight.

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